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ELECTRICAL METHODS OF SOLVING CERTAIN PROBLEMS OF THE DYNAMICS OF AIRCRAFT

C. L. Polisar, Candidate Tech Sci

/Figures are appended./

Contemporary electrical engineering is amply provided with means which can serve as a base for devising instruments suitable for solving systems of differential equations.

On the basis of schemes proposed by Prof L. I. Gutenmakher /1/ and theoretical and experimental investigations /2-6/, there have been developed, in the laboratory of Electrical Modeling, Power Engineering Institute of the Academy of Sciences USSR, new electrointegrators for the solution of systems consisting of six ordinary differential equations with constant coefficients, and systems consisting of 12 differential equations.

These electrointegrators are composed of amplifiers which are interconnected through conductances and capacitances.

The dependent variables of the network are the voltages U_i on the amplifier inputs. The assigned arbitrary initial conditions are simulated by charges on the condensers connected to the junction points of the network.

After inserting the voltage variation pattern against time into the amplifier inputs, a system of differential equations /1/ may be written:

$$\sum_{k=1}^{n} (A_{ik} + RCb_{ik}P)\, U_k + \psi_i(t) = 0 \qquad (1)$$

$$(i = 1, 2, \ldots, n),$$

where R — the coupling resistor,

C — the coupling condenser,

$p = \frac{d}{dt}$,

a_{ik}, b_{ik} — coefficients set up with the aid of dividers located on the amplifier outputs.

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The system of equations, whose solution is possible with the help of this integrator, has the form:

$$
\begin{aligned}
&a_{11}\, U_1 + b_{11}\frac{dU_1}{dt} + a_{12}\, U_2 + b_{12}\frac{dU_2}{dt} + \cdots + a_{16}\, U_6 + \\
&b_{16}\frac{dU_6}{dt} = F_1(t)_1 \\
&a_{21}\, U_1 + b_{21}\frac{dU_1}{dt} + a_{22}\, U_2 + b_{22}\frac{dU_2}{dt} + \cdots + \\
&a_{26}\, U_6 + b_{26}\frac{dU_6}{dt} = F_2(t), \\
&- \\
&- \\
&a_{61}\, U_1 + b_{61}\frac{dU_1}{dt} + a_{62}\, U_2 + b_{62}\frac{dU_2}{dt} + \cdots + \\
&a_{66}\, U_6 + b_{66}\frac{dU_6}{dt} = F_6(t).
\end{aligned}
\tag{2}
$$

The electrointegrator consists of blocks according to the number of differential equations in the system. Each block has an amplifier with a rectifier supplied from the city power line, a divider with connecting leads for setting the coefficients in each arm on the amplifier output, and a group of connectors.

The solutions obtained can be observed with the aid of a cathode-ray oscilloscope built into the integrator. Provision is also made for connecting a loop oscillograph.

The integrator has a rotating device which results in a periodic repetition of the solution.

As investigations showed [3, 4], a simple conversion of the given system of equations into triangular form is sufficient, but is not an obligatory condition for assuring that the auxiliary roots which are specified by the natural parameters of the amplifiers will not introduce instability, and furthermore, that the solution obtained for the actual system of equations of the circuit will be very close to a solution for the given system of equations.

The error in solving a series of problems on the new electrointegrator did not exceed 2-5 percent.

As an example, we shall present the solution of a system of equations for the longitudinal vibrations of an airplane under given initial conditions [7]. The analytical solution of this system was given in V. S. Vedrov's book The Dynamic Stability of an Airplane, 1938, pages 104-109.

A large series of solutions for various conditions characterizing longitudinal and lateral dynamic stability of an airplane was carried out on the integrator in a very short period of time (N. V. Korol'kov and I. A. Kazantsev participated in this work). As an illustration, let us examine the disturbing motion represented by the following coefficients:

Coefficients	Condition "a"	Condition "c"
C_D	0.036	0.036
C_L	0.2	0.2
$C_{D\alpha}$	0.105	0.105
$C_{L\alpha}$	4.2	4.2
$m\,\alpha$	0	4.23
$m'\alpha$	1.17	1.17
m_q	2.34	2.34

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The assigned system of differential equations for longitudinal vibrations of an airplane in nondimensional form is:

$$\frac{d\Delta\bar{V}}{dt} = -C_D\Delta\bar{V} - 0.5\, C_{D\alpha}\Delta\alpha - 0.5\, C_L\Delta\theta,$$

$$\frac{d\Delta\theta}{dt} = C_L\Delta\bar{V} + 0.5\, C_{L\alpha}\Delta\alpha - 0.5\, C_D\Delta\theta \qquad (3)$$

$$\frac{d^2\Delta\alpha}{dt^2} + \frac{d^2\Delta\theta}{dt^2} = -m_\alpha\Delta\alpha - (m'_\alpha + m_q)\frac{d\Delta\alpha}{dt} - m_q\frac{d\Delta\theta}{dt},$$

where V is the velocity of the center of gravity,

θ the angle between the tangent to the trajectory and the horizon,

α the angle of incidence:

$$\alpha = \delta - \theta$$

δ the angle of pitch.

In order to solve this system on the electrointegrator, it is reduced to a system of five differential equations of the first order by introducing new variables:

$$p\Delta\alpha = \frac{d\Delta\alpha}{dt} = U$$

$$p\Delta\theta = \frac{d\Delta\theta}{dt} = W$$

Oscillograms of the solutions of the given system of equations

$$\Delta\bar{V} = f_1(t);$$

$$\Delta\theta = f_2(t);$$

$$\Delta\alpha = f_3(t).$$

are shown in Figure 1 for condition "a" and in Figure 2 for condition "c."

A comparison of oscillogram "c" with the analytical solution showed that the error of the solution obtained by the integrator was within the limits of the thickness of the oscillogram lines.

The apparatus described makes it possible to determine rapidly the effect of changes in the parameters on the course of the process under investigation.

Considerably greater difficulties are encountered in studying longitudinal and lateral stability of an airplane with an autopilot. In these cases it is not always expedient or possible to carry out the modeling of the system in its entirety. Such an attempt may introduce considerable idealization, as a result of which the essential characteristics of the autopilot (nonlinearity, lag, etc.) will not be taken into account. It is more suitable to study a real autopilot on an airplane model.

The application, for this purpose, of mechanical stands in an "Oppel't" arrangement, and others, are characterized by one degree of freedom. Their motion is described by a second order equation alone. Nevertheless, even for simplified assumptions (see V. S. Vedrov's The Dynamic Stability of an Airplane), the motion of the airplane is described by a system of five differential equations.

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Under these conditions, the role of the test stand can be fulfilled by the electrical circuits and amplifiers indicated above, according to a scheme of direct current amplification, or with modulated AC amplifiers.

Figure 3 shows the principal diagram for studying the stability of an airplane with an autopilot which deflects the ailerons and control rudder corresponding to the angles of bank and yaw.

The system of differential equations describing the process under investigation has, in the general aspect, the form:

$$
\begin{aligned}
&p\,U_1 + a_{11} U_1 + a_{12} U_2 + a_{13} U_3 + a_{14} U_4 = 0;\\
&a_{12} U_1 + p\,U_2 + a_{22} U_2 + a_{23} U_3 = f_{\text{э}}(t);\\
&a_{31} U_1 + a_{32} U_2 + p\,U_3 + a_{33} U_3 = f_p(t);\\
&\qquad a_{42} U_2 + a_{43} U_3 + p\,U_4 = 0;\\
&\qquad\quad a_{54} U_4 + p\,U_5 = 0.
\end{aligned}
\tag{4}
$$

The values of the functions corresponding to the angles of bank and yaw are inserted into the autopilot through special converters. From the output of the autopilot through the corresponding converters, the following values are applied: on busbar 2 -- the right side of the equation, $f_{\text{э}}(t)$, proportional to the banking moments created by the ailerons during their deviation as a result of the reaction of the autopilot to a change in the angle of bank; on busbar 3 -- current proportional to the restoring moment of yaw $f_p(t)$ created by the control rudder during its deviation resulting from the reaction of the autopilot to a change in the angle of yaw.

In more complex cases, it is necessary to use electrical apparatus for solving nonlinear differential equations.

The data presented above makes it possible to assume that electrical circuits with amplifiers can serve as a test stand in design offices and research laboratories.

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/Appended figures follow:/

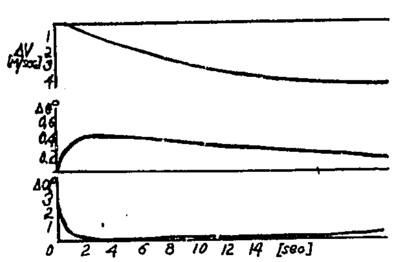

Figure 1

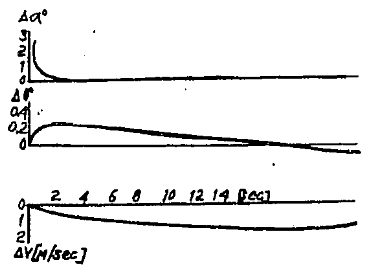

Figure 2

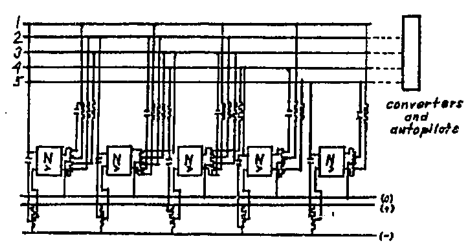

Figure 3

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